The Space Interferometry Mission

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Abstract. The Space Interferometry Mission (SIM) is a space-based long-baseline optical interferometer for precision astrometry. SIM will extend the reach of precision astrometry to cover the entire Galaxy, and will address a diverse set of topics in Galactic astronomy. It will also serve as a technology pathfinder for future astrophysics missions. The SIM architecture uses a 10-m Michelson interferometer in Earth-trailing solar orbit to provide 4 microarcsecond (μas) precision absolute position measurements of stars down to 20 magnitude. The corresponding parallax accuracy allows distance measurements to better than 10% accuracy at 25 kpc. SIM will allow us to measure absolute luminosities of many stellar constituents of the Galaxy with unparalleled accuracy. Calibration of indicators in the cosmic distance scale is an obvious application.

SIM will achieve a proper motion accuracy of about 2 μas/yr during its 5-year lifetime, equivalent to 10 m/s at 1 kpc. This sensitivity will allow SIM to perform an astrometric (reflex motion) search for low-mass planets around a large sample of nearby stars. Combining distances and proper motions measured using SIM with ground-based radial velocity data provides a powerful tool for stellar dynamics. Using samples of stars in the Galactic disk and the halo as tracers, SIM will address a variety of questions relating to the formation and dynamics of the Galaxy. In addition to precision astrometry, SIM will produce images with a resolution of 10 milliarcsec, equivalent to a diffraction-limited optical aperture of 10 meters. It will also demonstrate interferometric nulling with suppression of the on-axis starlight to a level of 10^{-4}.

In this paper we present selected topics from the SIM science program focusing on some specific astronomical questions to be addressed.

1. Introduction

The SIM architecture uses a 10-m Michelson interferometer optical interferometer operating in the visible waveband in Earth-trailing solar orbit. This mission will open up many areas of astrophysics, via astrometry with unprecedented accuracy. Wide-angle measurements, which include annual parallax, will reach a mission accuracy of 4 μas. Over a narrow field of view the relative accuracy is improved, and SIM is expected to achieve a mission accuracy of 0.25 μas. In this mode, SIM will search for planetary companions to nearby stars, by detecting the astrometric 'wobble' relative to a nearby ($\leq 1^\circ$) reference star.

The expected proper motion accuracy is around 2 μas/yr, corresponding to a transverse velocity of 10 m/s at a distance of 1 kpc.

In addition to precision astrometry, SIM will produce images with a resolution of 10 milliarcsec, equivalent to a diffraction-limited optical aperture of 10 meters (its scientific capability is limited primarily by the modest light collecting area). An example of an imaging target for SIM is a nearby active galactic nucleus with strong Hα line emission near its center. By imaging the Doppler-induced velocity structure of the line-emitting gas, SIM will probe the mass distribution in the very dense region near the central massive black hole.

SIM will also demonstrate interferometric nulling with suppression of the on-axis starlight to a level of 10^{-4}. This capability is primarily a technology demonstration of the proposed Terrestrial Planet Finder mission, but it will also have science applications. An example is imaging, using nulling mode to suppress the central star, of a dust disk around a nearby star.

Figure 1 shows the design for SIM, based on an architecture in which there is a single baseline vector. A summary of the key instrument and mission parameters is given in Table 1. The instrument and mission design are described in recent papers by Shao (1998) and Aaron (1998).

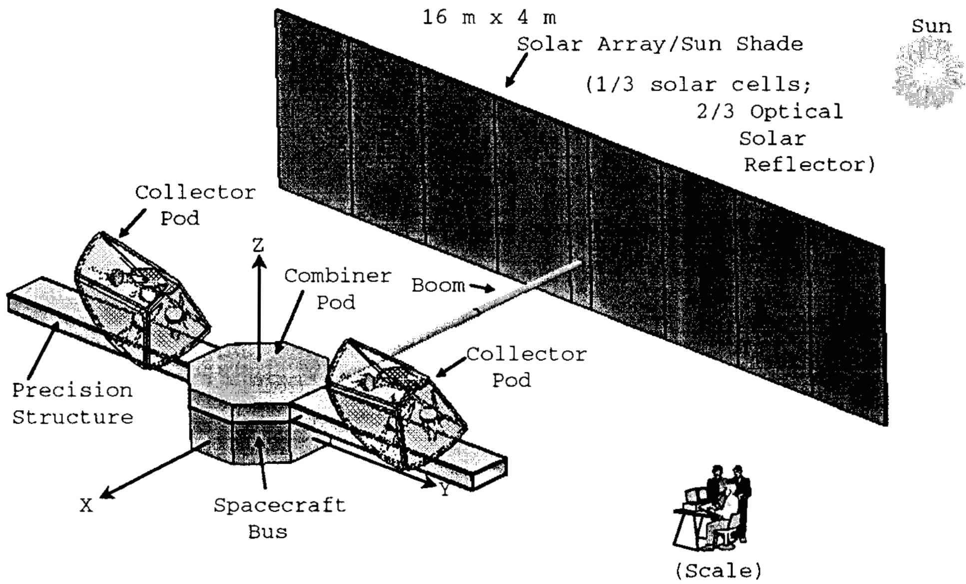

Figure 1. Overview of SIM conceptual design.

SIM is primarily a mission defined by a set of astrophysics goals. But it is an important technology stepping stone for future astrophysics missions, such as the Next Generation Space Telescope (NGST) and Terrestrial Planet Finder (TPF). Many key technologies needed by future missions will be demonstrated by SIM, then carried over directly or readily adapted. SIM is part of a NASA technology development plan which includes ground-based optical/IR interferometers, laboratory testbeds, flight verification of components, and space-based missions. The long-range goal of this program is to enhance the capability of future missions while reducing mission cost and risk. For more information on SIM, and the Interferometry Technology Program at JPL, visit our web site at: `http://huey.jpl.nasa.gov/sim`.

Table 1. SIM Instrument and Mission Parameters

Baseline	10 m
Wavelength range	0.4 - 1.0 μm
Observational Band:	400 - 1000 nm
Telescope aperture	0.3 m diameter
Astrometric Field of Regard (FOR)	$15° \times 15°$
Imaging field of view	0.3 arcsec
Detector	Si CCD
Orbit	Earth-Trailing solar orbit
Mission Duration	5 years (launch June, 2005)
Global (all-sky) astrometric accuracy:	4 μas mission accuracy
Astrometric Sensitivity	20 mag in 4 hours
Astrometry (narrow-angle)	0.25 μas mission accuracy
Proper motion accuracy:	1 μas/yr
Imaging Resolution	10 milliarcsec
Imaging Sensitivity (point source)	25 mag in 1 hour
Interferometric Nulling	Null depth 10^{-4}

2. SIM Astrometric Program Highlights

The astrometric capability of SIM will far exceed the accuracy of ground-based observations, or any other space mission in the near future, so the potential exists for unexpected results, as well as contributing strongly to known problems in stellar astrophysics, planet detection, and galactic dynamics.

Below we present only a selected topics from the science program focusing on specific astronomical questions to be addressed. This presentation is intended to highlight the breadth of the proposed SIM science program.

Searching for planets around other stars: The formation of planetary systems is a long standing problem, but poorly understood problem in astronomy. The discovery of planets around other stars using radial velocity techniques has brought this problem into sharp focus. SIM will contribute strongly to the testing of solar-system formation theories by searching for planets. It will be capable of detecting planets down to Earth mass around the nearest stars, and Jupiter-mass planets out to a kiloparsec.

Operating in its narrow-angle mode, SIM will monitor the reflex motion of the target star around the common center of mass, with respect to a local

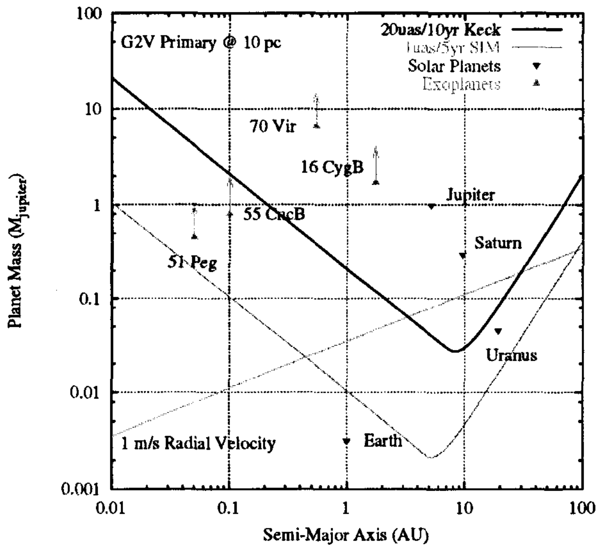

Figure 2. Planet searching with SIM by detecting reflex motion of the target star (solar-type at 10 pc), showing the capabilities of ground-based radial velocity measurements, the Keck Interferometer, and SIM.

frame of distant objects. The science interferometer alternatively observes the candidate star and distant background stars within about one degree on the sky. By carefully selecting those reference stars forming the local frame, repeated observations will lead to a very high relative positional accuracy of the science target with respect to this local frame. In its narrow-angle regime, SIM will reach a precision of about 0.25 μas during the mission lifetime. This corresponds to a detection of the reflex motion induced by an Earth-mass planets around the nearest few G-type stars. The two-dimensional astrometric information obtained then uniquely defines the orbital inclination of the companion, and hence a unique mass (since the distance is known accurately via parallax).

Large terrestrial planets orbiting nearby solar-type stars are readily detectable. SIM will search roughly 200 main-sequence stars for large terrestrial planets which formed as rocky cores in the region closer to their parent stars than the inner boundary of the ice condensation zones in their proto-planetary disks. Where feasible, orbital solutions and planet masses will be derived. Once one planet is detected, the search will be extended for evidence of additional planets in those systems.

Orbits of small stellar systems: Distances to globular clusters can be accurately determined by SIM — throughout the Galaxy. The spatial distribution and kinematics of the globular cluster system provides a powerful probe of the mass distribution of the Galaxy, the phase-space and metallicity distribution of the cluster system, the formation of the Galactic halo, and the evolution of the cluster system itself. Several authors have analyzed the globular cluster system with these aims in mind (Thomas 1989). All of these analyses have used angular positions, distances and radial velocities—4 of the 6 phase-space coordinates. Accurate proper motions determined by SIM can greatly enhance the power of such analyses by providing the final two phase-space coordinates.

Of about 150 known globular clusters, over 90% are within 30 kpc of the Sun (Harris 1996). Measuring the transverse velocity of these clusters to a level of 5 km/s requires a proper motion accuracy of 35 μas/yr, a relatively large signal for SIM. The number of stars required per cluster depends on the richness of the cluster compared to the background but probably an average of 5–10 stars is desirable to eliminate possible background stars or occasional stars with anomalous velocities. Almost all of the clusters have an adequate supply of red giant stars with $V < 18$. There are 25 satellites of the Galaxy with Galactocentric radii between 20 and 250 kpc and known radial velocities. Most of them should be easy targets for SIM.

Dynamics and evolution of binary stars: Compact objects in binary star systems can be studied with SIM. These objects serve as laboratories for exploring extreme physical conditions. Studies of the current binary parameters of such systems have provided the strongest evidence yet obtained for the existence of black holes and of gravitational wave radiation. The evolution of these systems is complex, due to the effects of mass transfer and mass loss. The origin of Type I supernovae, millisecond pulsars, low mass X-ray binaries, and globular cluster X-ray sources all involve unsolved issues in the evolution of compact binary systems. The combination of excellent spatial resolution and high sensitivity will enable SIM to determine the orbital parameters of these systems to unprecedented accuracy. The current dearth of definitive mass and orbit determinations suggests that even a modest number of SIM measurements will represent a breakthrough in this field.

The stellar mass-luminosity relation is fundamental to our understanding of both the mass distribution in the Galaxy and of stellar structure, particularly in determining the exact location of the hydrogen-burning limit. The M/L relation reflects the physics of stellar interiors. At present, the relation for solar-metallicity stars less massive than $0.5M_\odot$ is defined by only 20 stars. All are astrometric binaries, and the masses are determined to a typical precision of 20 to 40 %. Mass determinations for metal-poor stars are effectively non-existent. SIM can determine high-accuracy parallaxes and photocentric orbits for known, nearby, late-type spectroscopic binaries in both the general field and in clusters, achieving mass estimates with a precision of better than 2 %.

Dynamics of the local Universe: Local Group dynamical studies provide an understanding of the mass distribution and the structure in a typical collapsing group on 1 Mpc scales. Investigations of Local Group kinematics using radial velocities and distances have been conducted in the past by a number of researchers (see Peebles 1996 and references therein). SIM will enhance the power of these studies not only by providing more accurate distances but more importantly by providing proper motions for a number of galaxies in the Local Group. Each such measurement means that all six phase-space coordinates of the galaxy will be known and these measurements combined with the age of the Universe and constraints from linear perturbation theory strongly overdetermine the orbit for a given mass distribution.

Many of the nearby galaxies are clustered into groups (the main groups within 5 Mpc include IC 342, M81, NGC 4244, Cen A, Sculptor, M101). The dynamics of virialized groups can be used to probe the distribution of dark matter; the principal limitation to analyses of this kind is that redshift provides only one of the three velocity components of each galaxy. By measuring proper motions, SIM can determine the other two components and thereby dramatically enhance our understanding of the orbits and masses in nearby groups.

Rotational parallaxes of nearby spiral galaxies: SIM will provide a unique method of distance determination on scales our to a few Mpc, via 'rotational parallaxes'. Precise knowledge of the distances of nearby galaxies (to a precision of a few percent) is important for calibrating the cosmic distance scale, understanding the kinematics and dynamics of the local group, and comparing stellar populations in different galaxies.

SIM will eliminate potential major uncertainties due to luminosity-based distance indicators, since it is a single-step method. It will provide a direct calibration of the Tully-Fisher relation used to measure larger distances in the universe. The goal is to obtain rotational parallaxes to every large spiral galaxy with individual Population I stars bright enough to be within the observing limit of SIM. SIM will measure the distances of each of these galaxies to the limits set by systematic errors in radial velocity measurements, assumed to be 10 km/s, or in the proper motions. For the closer systems, this is easily accomplished, so for M 31 and M 33 the process could be made to be wholly self-consistent, thereby avoiding as many systematic errors as possible. To do that, SIM will need to determine the velocity curve through the range of radial distances as well as solve for a number of other parameters.

Astrometric gravitational microlensing events: Massive compact objects in the Galaxy may be a significant component of the dark matter inferred from dynamical considerations. Gravitational microlensing events are a tool to study these elusive objects. A significant number of such events have now been detected photometrically from ground-based surveys, though the results have raised a number of new questions. However, photometric events do not uniquely determine the mass of the lens – instead results must be interpreted in the context of a halo model (Alcock 1996).

SIM detects microlensing events via the astrometric signatures created in a microlensing encounter. Physical properties of the source and lens may be inferred directly from the encounter data. Boden et al. (1998) demonstrate the application of simulated microarcsecond astrometry to reconstruct the mass and kinematic properties of the lens – something not currently possible with the vast majority of photometric-only detections. Additionally, Paczyński (1998) describes applications of the technique to measure the masses of individual stars, and the measurement of stellar diameters. Of the three of these projects, the study of halo lenses is probably the most significant. Monitoring both photometric and astrometric observables over time yields an observable set that can be used to estimate lens and source parameters. While some parameters are amenable to narrow-angle techniques, SIM's wide-angle accuracy allows determinations of mass and distance for most Galactic bulge and LMC/SMC events.

3. Conclusions

The Space Interferometry Mission is part of NASA's Origins theme, and many of its science objectives are related to the Origins goals, including wealth of data concerning the pervasiveness of planetary systems (and sub-stellar companions) around nearby stars, and mass statistics of these systems. In addition, it will provide key data for a variety of questions in astrophysics, including:

- Searching for other solar systems, and studying the process of star and solar system formation
- Studying the mass distribution and evolutionary history of the Galaxy, using globular clusters and dwarf spheroidal galaxies as probes
- Calibrating distance and age indicators used for measuring the cosmic distance scale
- Directly measuring distances to spiral galaxies, independent of all luminosity-based distance indicators
- Characterizing dark matter in the Galaxy by observing microlensing events

The SIM Science Working Group (co-chaired by Deane Peterson and Mike Shao) has played a key role in defining science requirements for SIM. Their efforts have built on the efforts of earlier study teams, and individual astronomers who have explored the potential of microarcsecond astrometry. Only the highlights of the SIM science program are described in this paper. Many colleagues contributed to this work, including Michael Shao, Rudolf Danner, Jo Pitesky, and Jeffrey Yu. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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